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Piezoelectric Energy Harvesting from Raindrop Impacts in the Context of Bangladesh

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ABSTRACT

Due to the increasing demand of energyall over the world including Bangladesh, research on alternative energy resources in recent years has been increasing noticeably. Piezoelectric Energy Harvesting (PEH) technique can be used to capture vibration or mechanical stress to convert it into electrical energy.Raindrop possesses kinetic energy which creates mechanical stress when it falls on piezoelectric material and this mechanical stress is converted into electrical energy. In this work, open circuit voltage response of PREH (Piezoelectric Raindrop Energy Harvester) composed of two different piezoelectric materials Lead Zirconate Titanate (PZT) and Polyvinylidene Fluoride (PVDF) have been studied using COMSOL Multiphysics software. The output voltage depends on the harvester dimensions and pressure of rain droplets which are calculated precisely in prospect of Bangladesh.

Keywords: Raindrop energy, Piezoelectricity, PVDF, PZT, COMSOL Multiphysics

1. Introduction

Energy is a burning issue of present world including Bangladesh. On one hand the conventional energy sources are declining, on the other hand the demand of energy is increasing day by day. This is the reason why alternative energy sources are grabbing our attention. While looking for alternative energy sources we have to keep in mind that these sources need to be environment friendly and sustainable. Bangladesh is a monsoon country. Here almost all the year round it rains. Raindrops, when fall from a high height contain a sufficient amount of kinetic energy. One way of converting this energy into electrical energy is to store the water at certain elevation and then to convert this potential energy into kinetic energy which can be converted into electrical power through hydro turbines which is the concept of hydro power generation [1]. But this method has several limitations. It is quite costly and not always possible to build hydro power plant in all places. Another way to harness energy from raindrops ispiezoelectric devices. As raindrops fall on these devices, mechanical stress is created which is converted into electrical power. This method isgreener and cost effective especially for a country like Bangladesh.

In Bangladesh, solar is the main alternative resource at present; but in rainy days solar modules cannot work and in those days the Piezoelectric Raindrop Energy Harvester (PREH) can be a good source of energy.

2. Theoretical Overview

2.1. Piezoelectricity and Piezoelectric Materials

The phenomenon of electric charge generation when a transducer surface is subjected to mechanical stress or vice versa is known as piezoelectric effect. That is when the transducer is brought within an electric field it produces mechanical stress. Piezoelectric transducers work interactively with mechanical and electrical variables. When a piezoelectric material is faced with mechanical stress it produces electrical charges. When these charges are collected by two different electrodes an electric potential across the material surface is obtained. Piezoelectric materials are non-conducting and their ability of piezoelectricity depends on their crystalline structure. Quartz, tourmaline crystals, ceramics and some other

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organic materials exhibit piezoelectricity due to the absence of centre of symmetry in their structures. Generally Lead Zirconate Titanate (PZT) and such other types of ferroelectric ceramics are used in Piezoelectric Raindrop Energy Harvester (PREH). It has large relative permittivity and high charge sensitivity. PZT is extremely brittle which is a big limitation to use it as harvester as fatigue may occur due to high frequency cyclicloading [2]. It is heavy and toxic as contains Lead. PZT-2 is a hard material which can withstand heavy mechanical stress compared to soft PZT material. Organic material Polyvinylidene Fluoride (PVDF) exhibits considerable flexibility when compared to PZT [3]. PVDF is mainly used in applications where a higher degree of mechanical flexibility and optical transparency are required [4]. It is corrosion resistant and can withstand stress without being prone to fatigue. PVDF has lower values of strain Coefficient (d_{31}) and and coupling coefficient (k31) than of PZT [5]. But PVDF is lightweight and environment friendly. Kynar 720 type of PVDF has high tensile modulus and relative permittivity.

Table 1: Comparison of piezoelectric properties

Property	Unit	PZT-2	PVDF (Kynar 720)
Density, ρ	kg/m^3	7600	1780
Relative permittivity, $€_r$s	-	270	12
Tensile modulus	MPa	83	2200

It has low water absorption value (0:03%) [6]. When the material surface in subjected to vibration or pressure, mechanical stress is induced in it. This in turn provides an electromotive force that generates electric impulse. The force causes deformation of internal lattice structure of the material which is responsible for charge separation of positive and negative ions and formation of small dipoles.

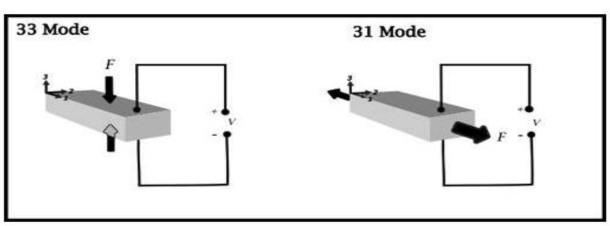

Fig. 1: Different coupling modes of operation of piezoelectric material [7]

The coupling method of a piezoelectric device contributes to the portion of energy harvested using it for useful purpose (Fig.1). 31 mode is the coupling method where the direction of applied force is perpendicular to the polling direction of electrodes. In 33 mode the direction of force is parallel with polling direction. 31 coupling mode is generally used but it has a lower value of coupling coefficient (1) than 33 mode.

$$K = \sqrt{\frac{electrical\ \ energy\ \ stored}{mechanical\ \ energy\ \ stored}} \qquad (1)$$

2.2. Harvesting energy from raindrops

Raindrop energy is a renewable energy yet to be acknowledged. Raindrop at a significant height possesses potential energy. When it falls down at certain velocity the potential energy is converted into kinetic energy. This great amount of kinetic energy can be implemented for useful purpose. Piezoelectric devices can be used as a collisional surface for the drop and a fraction of the kinetic energy that drop contains will produce vibration that is a form of mechanical energy. This can be converted into electrical energy efficiently (Fig.2).

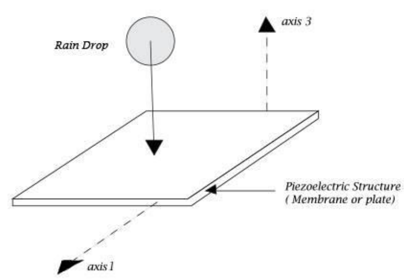

Fig. 2: System for raindrop energy harvesting [6]

Rain droplets can be of various sizes and the behavior of a droplet on impact on solid surface depends very much on its diameter. Droplets of maximum 4.5 mm diameter can be considered to have spherical shape while colliding at surface. Larger droplets can take more of a cylindrical form depending on the air resistance and wind speed. The height to width ratio is close to 0.5. When a rain droplet collides at a solid surface any one of the following three phenomena can occur; (1) Bounce, (2) Spread, (3) Splash (Fig.3). Droplet can either bounce completely or partially leaving water residue. Another chance is that it can spread on the surface smoothly or after impact it can break into small parts which is called splash. Last case scenario is a disintegration process. A raindrop energy harvester can demonstrate with all or a combination of these mechanisms. But generally spreading and splashing of droplets are matter of

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interest [5]. Studies show that splashing mechanism is the dominating impact [1].

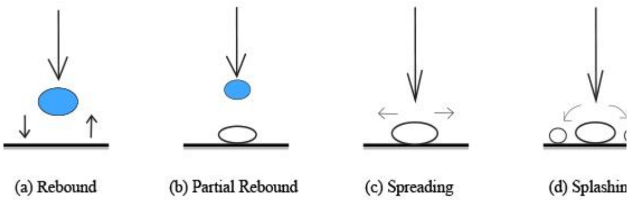

Fig. 3: Water droplet impact on solid surface [4]

Probability of deposition or splashing can be calculated from constant K (2); which depends on the solid surface roughness and layer thickness [9]. If the value of K>57.7 then splashing will occur otherwise only deposition will occur [10]. Splash causes significant amount of energy loss. Larger diameter of droplet impact without splashing generates greater amount of vibration. Thus more output power can be obtained.

$$K=\sqrt{We} \times \sqrt[4]{Re} \quad (2)$$

$$\text{Reynolds number, } R_e = \frac{inertial\ force}{viscous\ force} \quad (3)$$

$$\text{Weber number, } W_e = \frac{fluid\ inertia}{surface\ tension} \quad (4)$$

The impact of water droplets depends on surface inclination. For horizontal surface water drop effect depends on surface material properties, impact velocity, droplet viscosity, droplet surface tension an and droplet size [4], [11]. Maximum spread of drop is larger in glass surface than wax or Polyvinyl Chloride (PVC). Maximum amount of spread as well as the spreading velocity increases with increase in impact velocity. Impact of droplet on inclined surface depends on properties of droplet material; such as density, surface tension and viscosity [12]. Bouncing of droplets occurs only on wax or rough glass. Moreover droplet temperature or surface condition has no effect on tendency of bouncing or spreading of droplets.

Whereas rougher surface will trigger splashing of droplets near splashing conditions line [13]. Rain drop held at a certain height above ground has potential energy. When it falls below the potential energy is gradually converted into kinetic energy. Kinetic energy of water droplet increases with increasing velocity. At equilibrium stage it can be expressed being related to droplet velocity and size (5). Whereρ_w is the density of fluid, r is radius of droplet and v is velocity at equilibrium stage [4], [14].

$$Kinetic\ energy\ of\ raindroplet, E_{KE} = \frac{1}{2}\rho_w(\frac{4}{3}\pi r^3)v^2 \quad (5)$$

When a rain droplet falls from a certain height on a piezoelectric harvester it develops a mechanical stress. A fraction of kinetic energy the droplet possesses is converted as impact pressure on the piezoelectric surface.

$$Impact\ pressure, P = \rho C V_T \quad (6)$$

Where ρ is water density, C is speed of sound in water and V_T is terminal velocity of the falling raindrop [15]. Both water density and speed of sound in water depends on the temperature of the atmosphere. When a raindrop is falling through the atmosphere, it is subjected to two external forces; one is the gravitational force i.e weight of the raindrop and the other one is the air resistance or drag of the raindrop. The drag force which acts vertically in the upward direction is,

$$F_{air} = \frac{1}{2}\rho_a C_d {V_T}^2 \quad (7)$$

Where ρ_a is the air density, C_d is drag coefficient and V_T is terminal velocity of raindrop. The gravitational force which acts vertically in the downward direction on the raindrop is,

$$F_{gravity} = (\frac{4}{3}\pi r^3)\rho_w g \quad (8)$$

Where r is the radius of the raindrop and ρ_w is the density of water. When these two forces become equal, the raindrop falls in a constant velocity which is the terminal velocity, V_T. From the equations (7) and (8) above,

$$V_T = \sqrt{\frac{2mg}{\rho_a A C_d}} \quad (9)$$

3. Rainfall scenario in Bangladesh

3.1. Overview of monsoon season in Bangladesh

In Bangladesh it rains almost all the year round except in the months of winter which are mainly November, December and January. June, July, August and September (JJAS) these months are considered the monsoon season here. Heavy rainfall is observed in this period all around the country. Solar radiation is significantly lower on this time. Hence valid operation of solar energy harvesting devices is hindered. According to the rainfall data by Bangladesh meteorological department raindrop energy harvester can be a great replacement (Fig.4). Prior to monsoon season March, April and May are summer time. Bangladesh is straddled in the tropic of cancer. In the summer time solar radiation at great

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amount is obtained in the South East Asia region on this time.

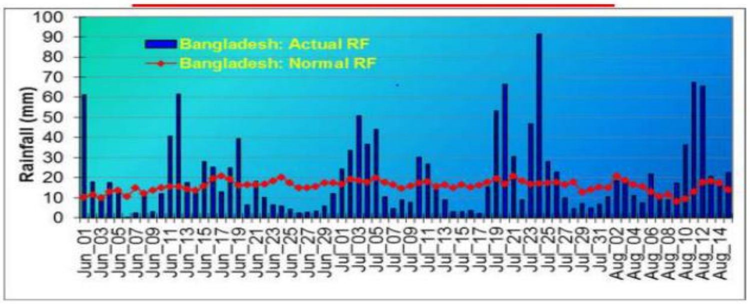

Fig. 4: Rainfall in Bangladesh – Monsoon season 2017 [16]

The air above the land is heated and rises up in the atmosphere. The water of upper level of Arabian Sea and Bay of Bengal is also heated and expands up at the atmosphere. These months are autumnal months for the Indian Ocean at the south of the equator. During this period the ocean remains cool and the dense air gathers around the ocean surface. This differential heating leads to Carnot cycle; producing massive cool aerial current from the Indian Ocean towards the hot land mass of South East Asia [5]. While passing over the Arabian Sea and Bay of Bengal, the cool dry air picks up warm, tropical vapour thus becoming moist air. Consequently the air gets warm and rises upwards. It further picks up warm vapour from the upper part of atmosphere. As the unsaturated air rises up, it gradually cools down and reaches a relative humidity of 100%. This saturated moist air, condenses around dust or any other particle (condensation nuclei) and the small droplets become visible as clouds. If the vapour further condenses on the cloud then droplet size increases. This vapour condensation releases latent energy which warms up the air pushing it further upwards; providing space for more wet air to come in from the sea. This is the process of growth of dark monsoon clouds. The massive cloud conveys northward and branches into a number of streams. These streams sweep towards forested areas at first when the droplets are transformed into raindrops and rainfall begins. One such stream moves towards Sumatra and another one moves towards the north along the forested coast of Arakan emerging into Assam and Bangladesh. According to recent studies about future rainfall prospect in Bangladesh in the year of 2020 rainfall scenario will remain almost constant (Fig.5). Handsome amount of rainfall will occur on the monsoon season. If 15 rain droplets of 5 mm diameter falls on a square flat surface, that is 900 raindrops in a minute the impact energy equals to 0.18 Watts [5].

3.2. Raindrop sizes and impact pressure

Generally, raindrops sizes vary from 0.1 mm to 5 mm. In some rare cases, raindrops upto size 8 mm occur. But raindrops larger than that tend to break down due to collision with neighboring particles. Majority of raindrop size ranges from 2.38 mm to

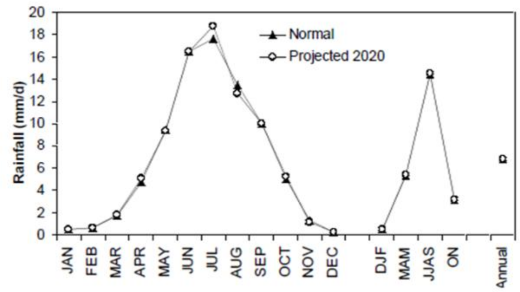

Fig. 5: Rainfall projection over Bangladesh in the year 2020 with historic (normal) data [17]

4.75 mm. Droplets of this range are ideal for PREH as they cause deposition without parting into small fractions. Moreover, droplet of 4.5 mm diameter takes the shape of a sphere while falling. And it is ideal for the harvester purpose. The impact pressure of a raindrop as it falls on the piezoelectric surface can be calculated from equation (6). Density of water droplet depends on the temperature of the atmosphere. During the monsoon season temperature all around Bangladesh varies from 28°C to 34.2°C. [16]. The average temperature is approximately 28.2°C. At this temperature the density of water is 996.175 kg/m3. Speed of sound in water increases with increase in water temperature. It is calculated to be 1500 m/s at 28.2°Cfor a 4.5mm raindrop. The terminal velocity is calculated to be about 10.38 m/s as a droplet of this size is projected on a circular area upon the surface. The impact pressure for a 4.5 mm raindrop is calculated to be 15.51Mpa in the context of Bangladesh.

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Table 2: Rain drop size assumption [18]

Bibliographic entry	Result (w/surrounding text)	Standardized Result
“Precipitation.” Earth Science.Illinois: Heath, 1999	“A raindrop may have a maximum diameter of 0.25centimeter.”	2.5 mm
“Rain.” EncyclopediaEncarta.1st ed.CD-ROM.New York: Microsoft,2000.	“Raindrops generally have a diameter greater than 0.5mm (0.02 in.). They range in size up to about 3 mm(about 0.13 in.) in diameter.”	0.5–3 mm
Davis, Neil T. “Rain drop Size Article #236.” Alaska Science Forum.28 June1978.	“The 4 mm maximum diameter of raindrops probably results because raindrops larger than this size tend to break up when colliding with other large raindrops.”	< 4 mm
“Characteristics of Particles and Particle Dispersoids.”Handbook of Chemistry and Physics.62nd Edition. New York:CRC,1981	“Chart”	0.5-10 mm
Formation of Raindrops.Encyclopedia.com.	“Raindrops vary in size from about 0.02 in. (0.5mm) to as much as 0.33 in.(8 mm) in thunderstorms.”	0.5–8 mm

4. Simulation and analysis

4.1. Design methodology

Finite element simulation of PREH made of PZT-2 and Kynar 720 individually is done using COMSOL Multiphysics. Arectangular solid film of dimension 16mm×7mm×0.25mmis designed as the PREH. The entire lower surface is fixed to the ground. It serves as the ground electrode with potential of 0 V. Coupling mode 33 is used and the upper surface of film is considered as the other face of electrode. The initial potential of this electrode is 0 V.

Boundary load is applied on a circle of 2.25 mm radius

Although 150 V peak value impulse is obtained; the average value of output potential varies almost similarly within and outside the projected area of rain droplet (Fig.10).

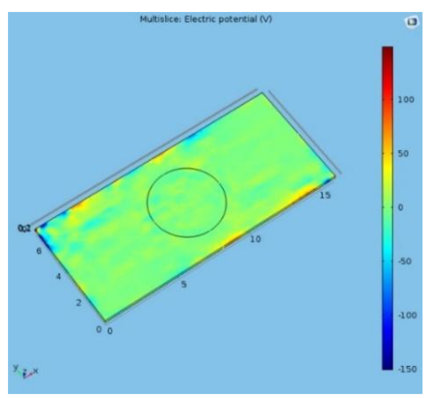

Fig. 10: Electrical potential on the surface of PVDF solid film

4.2. Graphical analysis

Graphical analysis of average electrical potential distribution along the length of both the solid film harvesters is performed for comparison. In the PZT

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harvester the output potential varies from -2.5 Volts to 2 Volts along the length (Fig.11). Absolute maximum potential which is 2.5 Voltsis obtained at the inner edge of the projected area of boundary load. In the PVDF harvester it is found that the output varies from -27 Volts to 15 Volts along the

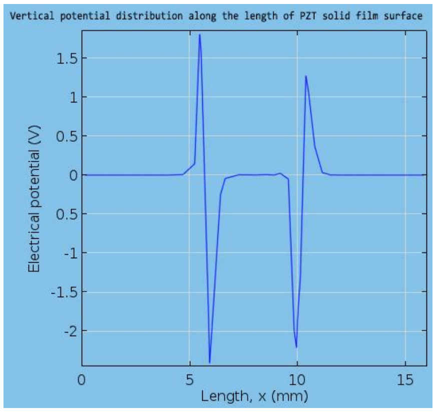

Fig. 11: Average voltage distribution on the PZT solid film along its length

length (Fig.12). Absolute maximum potential which is 27 Volts; is obtained close to the outer edge of the projected area of boundary load. Both the simulation are done varying only the piezoelectric material which leads to a comparative study of rain drop impact on Piezoelectric Rain Drop Energy (PREH) harvester made of PZT and PVDF. The absolute maximum electrical potential obtained from PZT PREH is 2.5 Volts. And the absolute maximum electrical potential from PVDF PREH is 27 Volts. As all other parameters were same for both the simulations, it can be stated that PVDF PREH provides better output than PZT PREH.

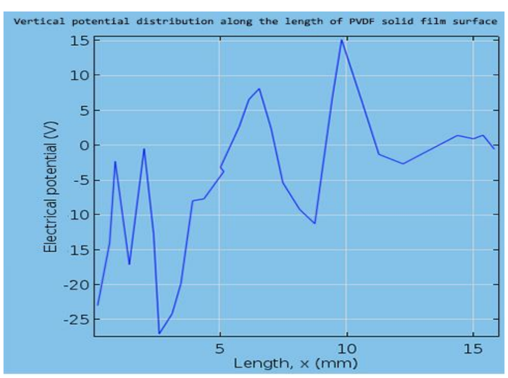

Fig. 12: Average voltage distribution on the PVDF solid film along its length.

5. Conclusion

In this paper an alternative green energy source has been explored. Bangladesh is a monsoon country. Here it rains almost all year round hence raindrop energy harvesting is a potential source of energy. In monsoon season, when existing renewable energy sources like solar cells cannot work properlyit can be a good alternative. It is a green source of energy. As only a fraction of kinetic energy possessed by raindrop is used, it can be considered for sustainable operation. In this work, two PREH have been designed using two different materials; one is Lead Zirconate Titanate (PZT) and the other one is Polyvinylidene Fluoride (PVDF). PVDF is comparatively more environment friendly than PZT as PZTcontains lead but PVDF is organic. Solid film harvester of film harvester of rectangular shape for both the materials of 16mm × 7mm × 0.25mm dimension is chosen. It is able to withstand the boundary load i.e. the impact pressure of one optimal sized raindrop which is calculated to be approximately 15.51 Mpa for Bangladesh. Coupling mode -33 ensures more uniform stress distribution which generates uniform average electrical potential. From PVDF harvester, electrical potential of -27V to 15 V has been found whereas electrical potential of -2.5V to 2V is obtained from PZT harvester. It draws the conclusion that PVDF harvester performs better than PZT harvester as it is both environment friendly and provides greater value of open circuit output voltage.

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